Thermoelectric Generators for Defense Applications

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Presenter: John C. Bass

Sponsor: TACOM-ARDEC, Picatinny Arsenal
TRI-SERVICE POWER EXPO 2003

16 July 2003

Agenda

- Background in Thermoelectrics
- Picatinny Program
  - Radio Isotope Program
  - Milliwatt Generators
  - Molten Salt Generator
  - Watt Generator
  - Swedish Generator
- Advanced Materials
  - Quantum Well Background
  - Recent Test Program
- Summary

Picatinny SBIR Program

Alternative Energy Source for Illumination

- Mortar Site Illumination
  - Tritium Fueled RTG
  - Fossil Fueled Generator
  - Phase Change Heat Source
- 1-2 Watt Generator
  - Battery Replacement
- Generators Up to 25 Watts
  - Battery Charging
  - Logistic Fuel

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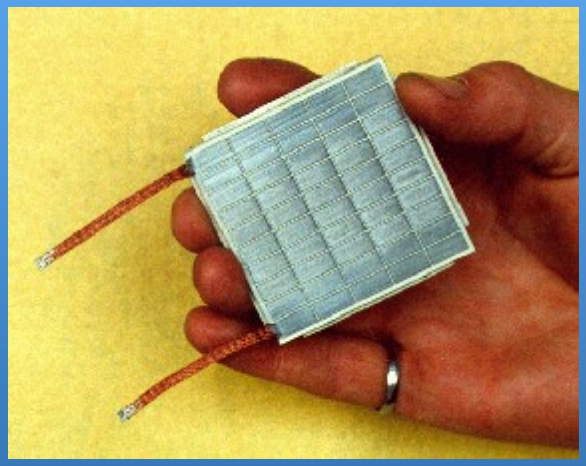
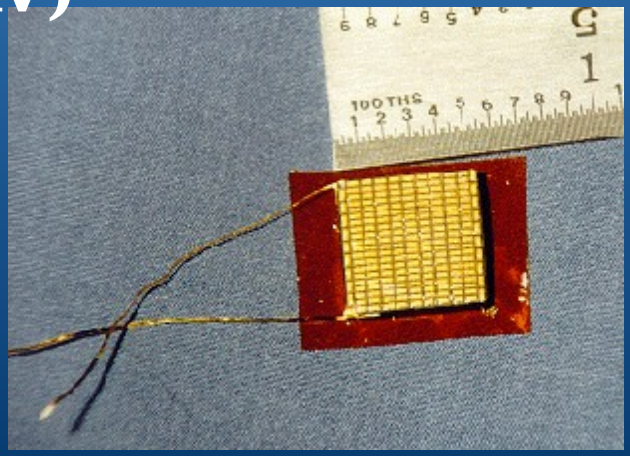
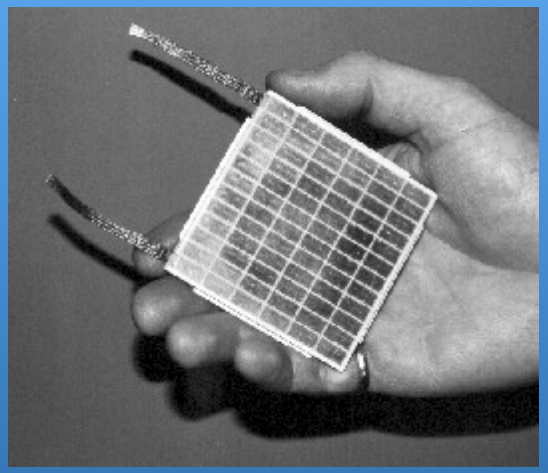
Products

HZ-14



800 milliWatt Modules for Micro Air Vehicle (MAV)

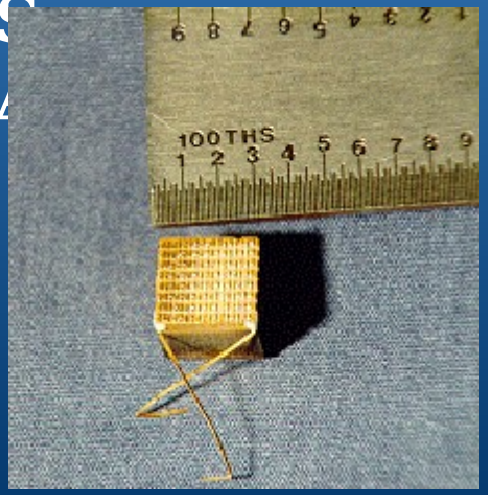




HZ-20

40 milliWatt Modules for S

A



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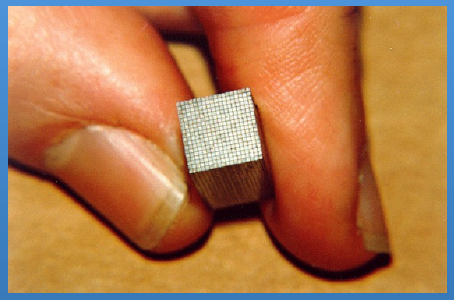
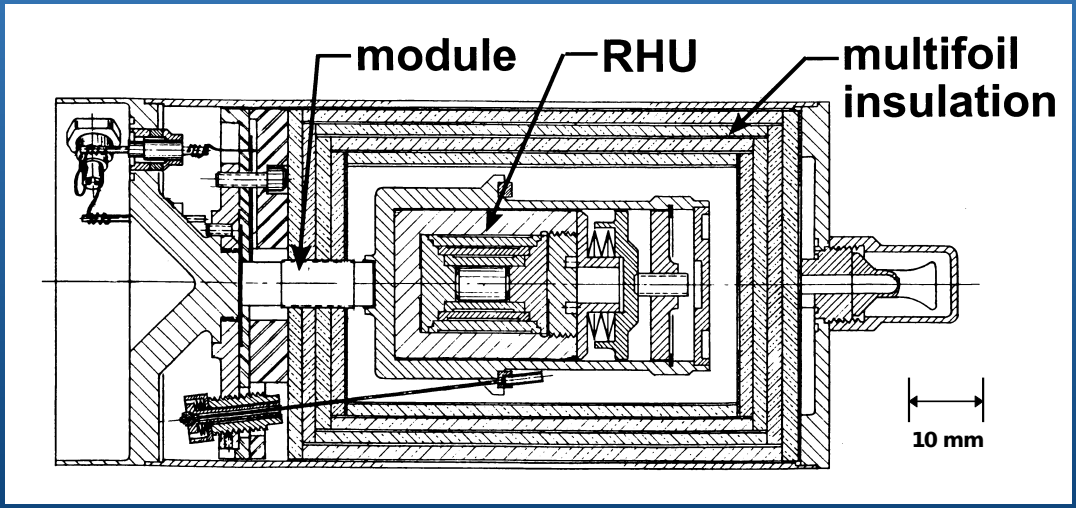
Army's Needs

- Replacement for radioluminescent lamps
- Battery replacement for small electronics associated with indirect fire weapons
- Portable battery charger/battery replacement for soldier power

Phase I - Radioisotope Generator

- In development for NASA/DOE for Mars surface weather station network
- PHU: 1 W Pu^{238}
- 40 mW output





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Driving Factors

- Use logistics fuel
- Rugged, reliable, long life
- Minimum specific power (W/kg)
- Minimum specific energy (W-hr./kg)
- Minimum specific volume (W-hr/1)
- Low price, low operating & support cost
- Environmentally friendly

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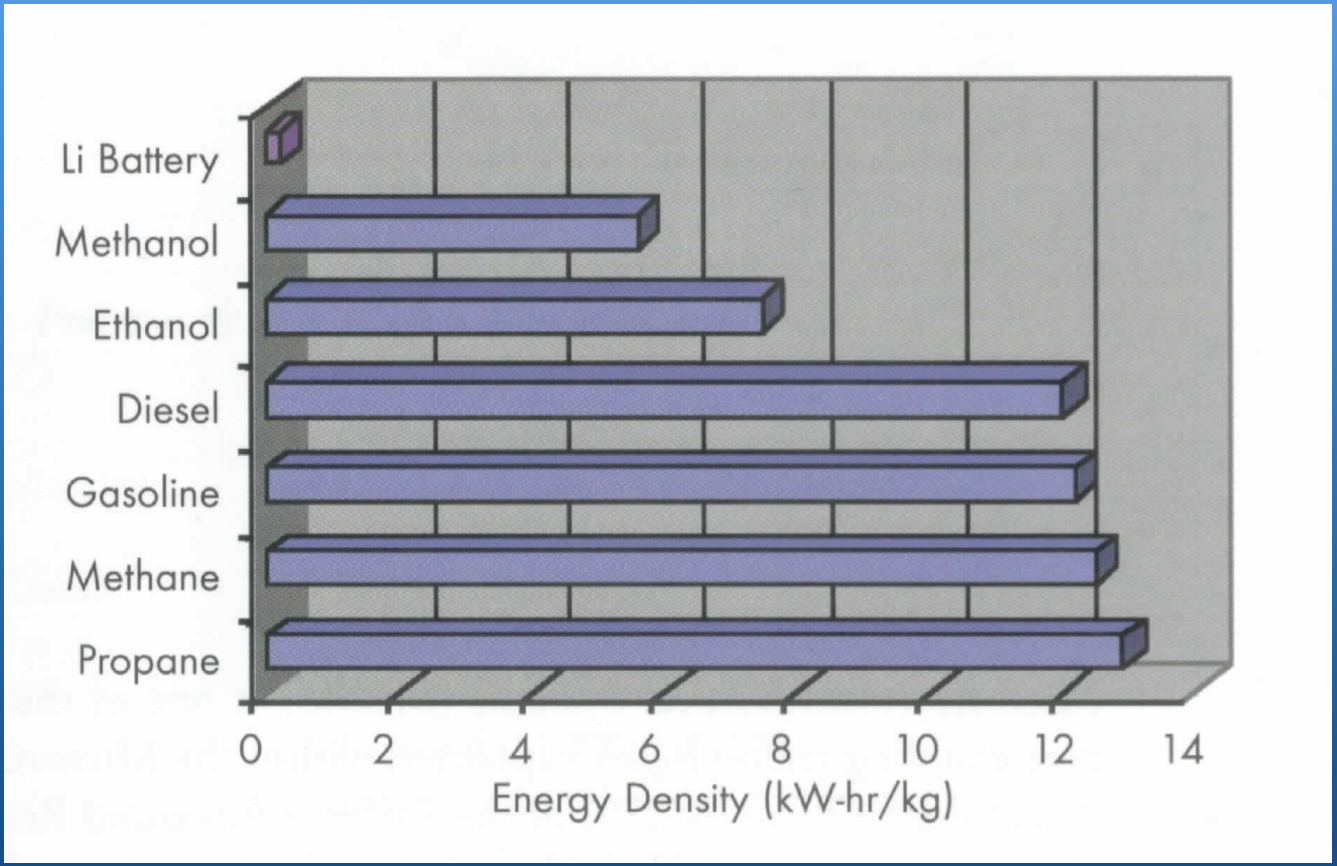
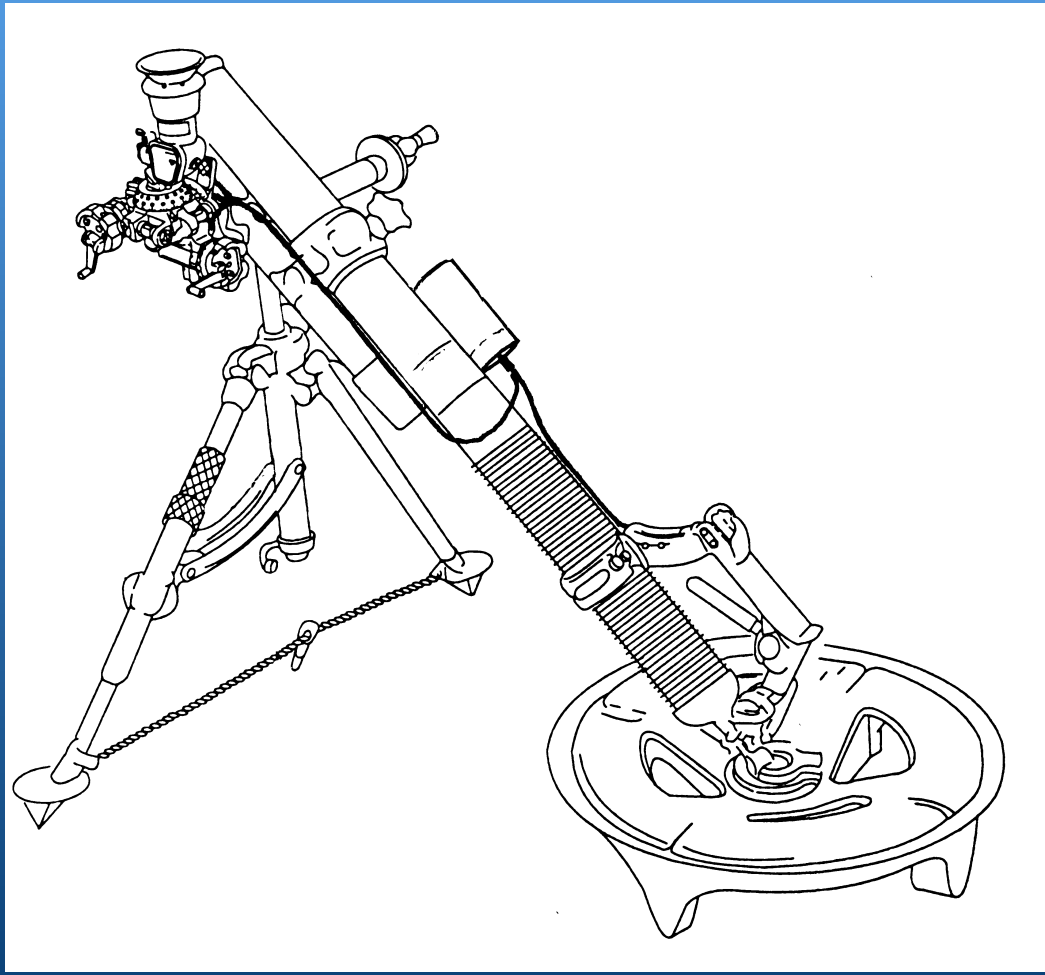
Generator vs. Battery



Phase I – Example Application

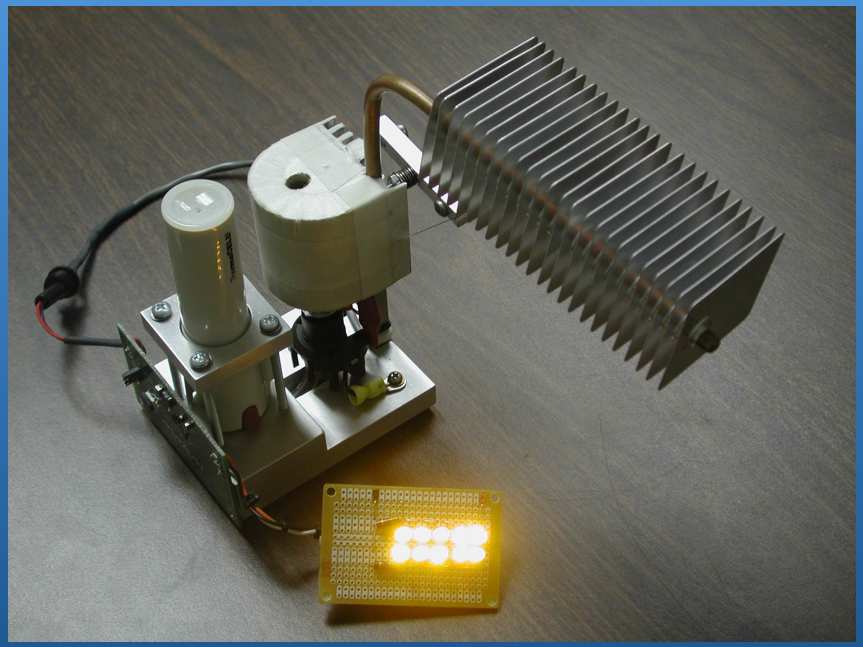


Task 7 – Tritium Heat Source Development

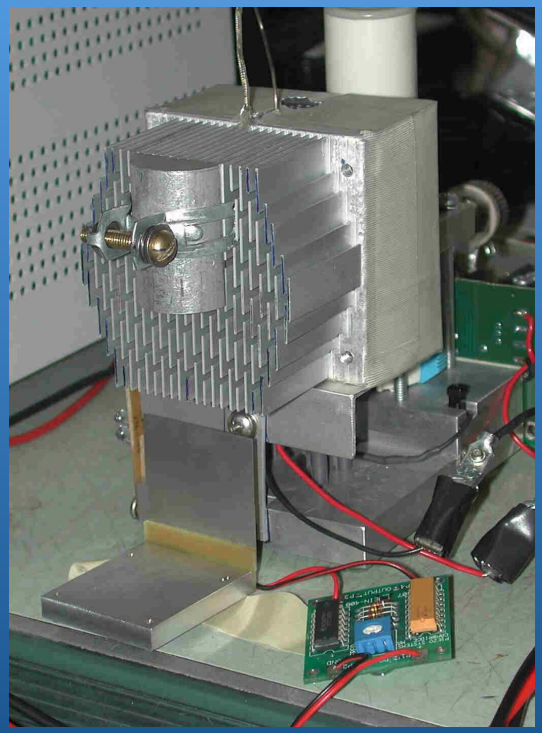
It was determined in the Phase I Option that radioisotopes appear not to be economically viable in this application, and so this task has been put on lowest priority.

Task 5 – Milliwatt Generator

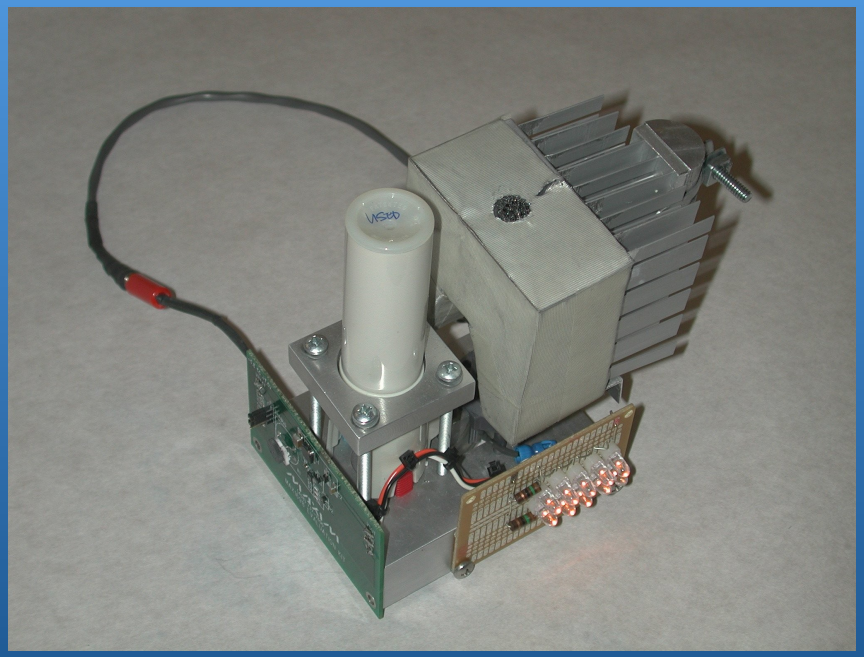
- Design (module)
300 mW
- Actual power
360 mW
- Generator output
5V
- T_H/T_C 260ºC
/ 70ºC
- Fuel consumption 40
mg//min
- Input heat
33 W



Task 5 – Milliwatt Generator



Generator #5B



Generator #6 & #7

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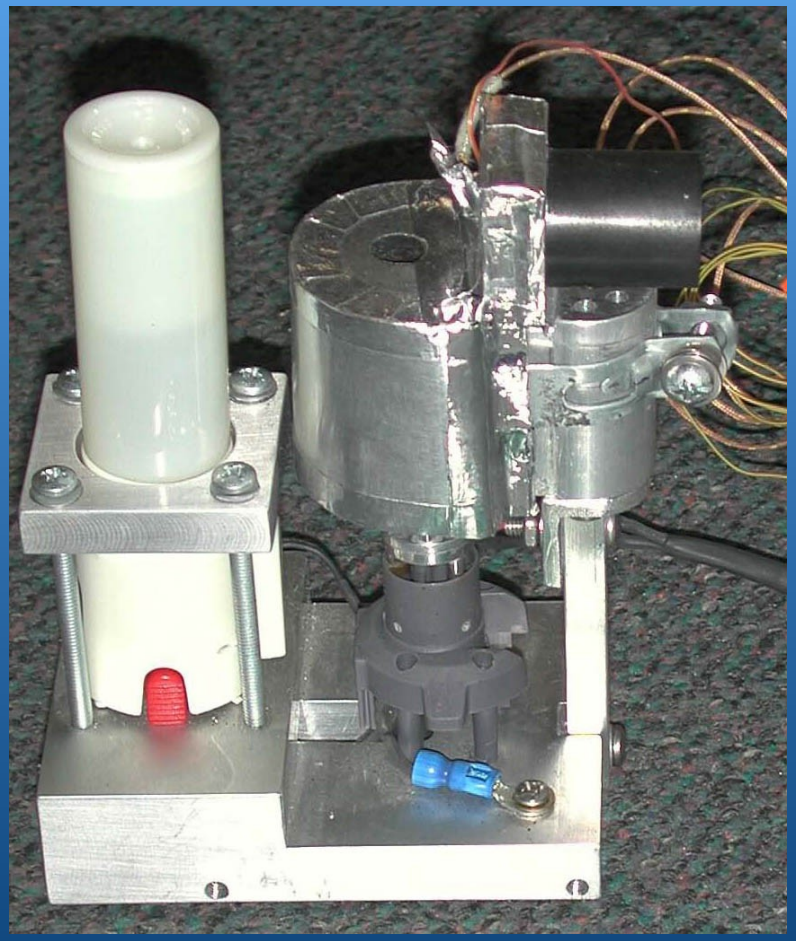
Task 5 – Milliwatt Generator



Generator #8

Task 5 – Milliwatt Generator

Generator	Cold Side Heat Exchanger Weight, Grams	
#4	151.8	
#5A & #5B	155.4	
#6 & #7	100.7	
#8	aluminum foil fan total	21.7 15.5 37.l2

Task 5 – Milliwatt Generator

unit	Description	date of 1st run	T_H °C	T_C °C	P_{net} watts
Gen'r #1A	HZ-2 module, cigarette lighter heat source, chip cooler fins sink with fan	24JUL01	102	32	- 0.52
Gen'r #1B	HZ-2 module, soldering torch source, chip cooler fin sink, 5V fan at 5V	18JUL01	246	63	1.10
Gen'r #1C	HZ-2 module, soldering torch source, chip cooler fin sink, 12V fan at 5V	18JUL01	252	50	1.25
Gen'r #2	HZ-2 module, soldering torch source, heatpipe sink	20JUL01	226	64	1.42
Gen'r #3A	MAV module†, hair curler source, chip cooler fin sink, 5V fan at 5V	27AUG01	207	32	- 0.67
Gen'r #3B	MAV module†, hair curler source, chip cooler fin sink, 12V fan at 5V	25JUL01	212	35	0.15
Gen'r #4	MAV module*, hair curler source, heatpipe sink	17DEC01	246	45	0.33
Gen'r #5A	MAV module*, hair curler source, aluminum fin natural convection sink	11OCT02	249	52	0.28
Gen'r #5B	MAV module*, hair curler source, same finned sink with piezo fan	13OCT02	233	54	0.35
Gen'r #6	MAV module*, hair curler source, second Al fin natural convection sink	25OCT02	235	49	0.35
Gen'r #7	MAV module*, hair curler source, graphite foam hot side HX (all of previous had a Cu block hot HX), second Al fin natural convection sink	26SEP02	272	55	0.35
Gen'r #8	MAV module*, hair curler source, graphite foam hot side HX, aluminum foam cold side HX with 5V fan	13FEB03	321	63	0.23
Gen'r #9	MAV module*, intended for Altex diesel heat source, graphite foam hot side HX, Al foam cold side HX with 5V fan	09JAN03	--	--	--

† same module built for Virginia Tech for the DARPA Micro Air Vehicle (MAV) program; designed for 0.8mW.
* same crossection as modules built for the MAV program but 3.9mm thick.

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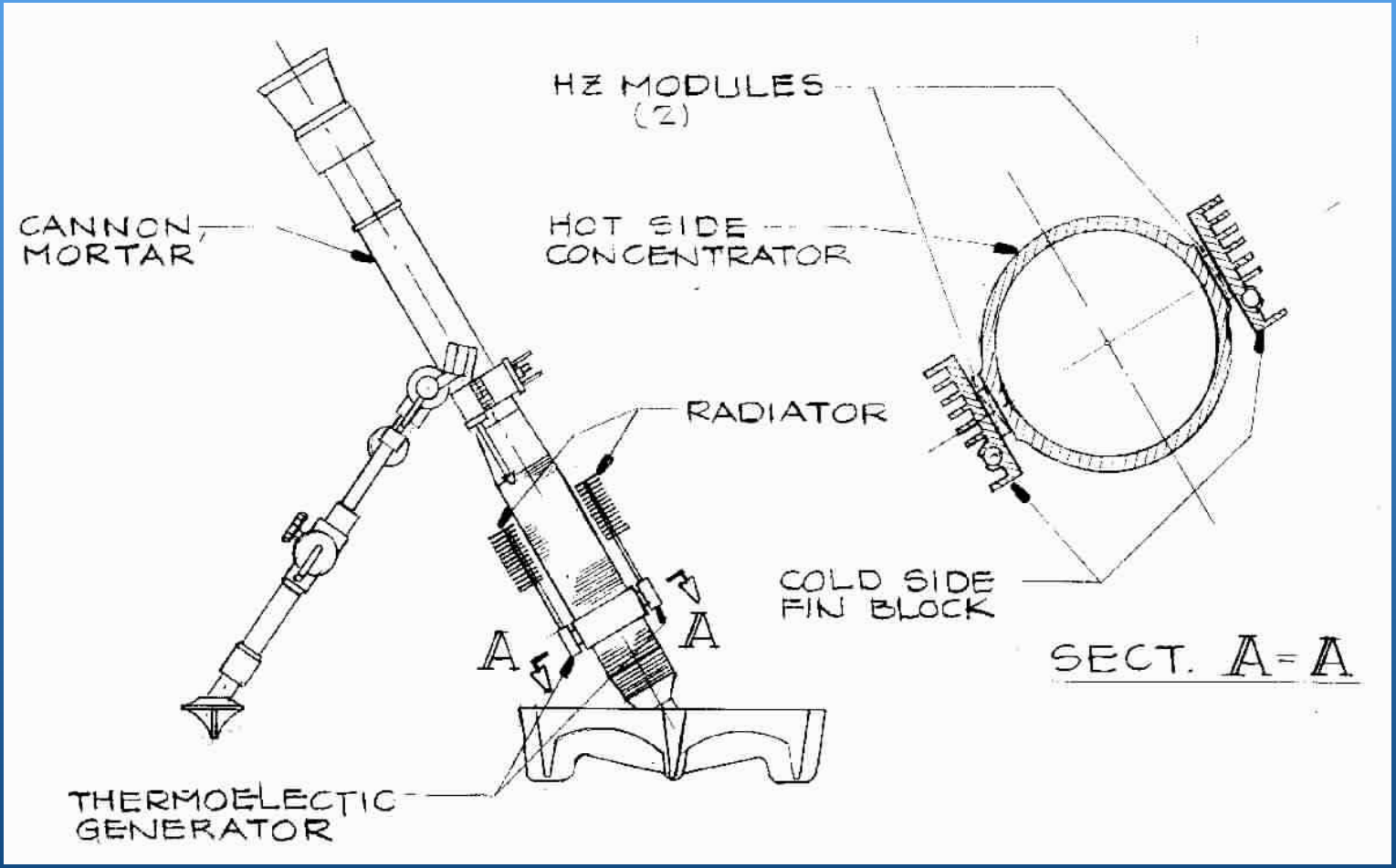
Task 5 – Milliwatt Generator
Generator #8 Features

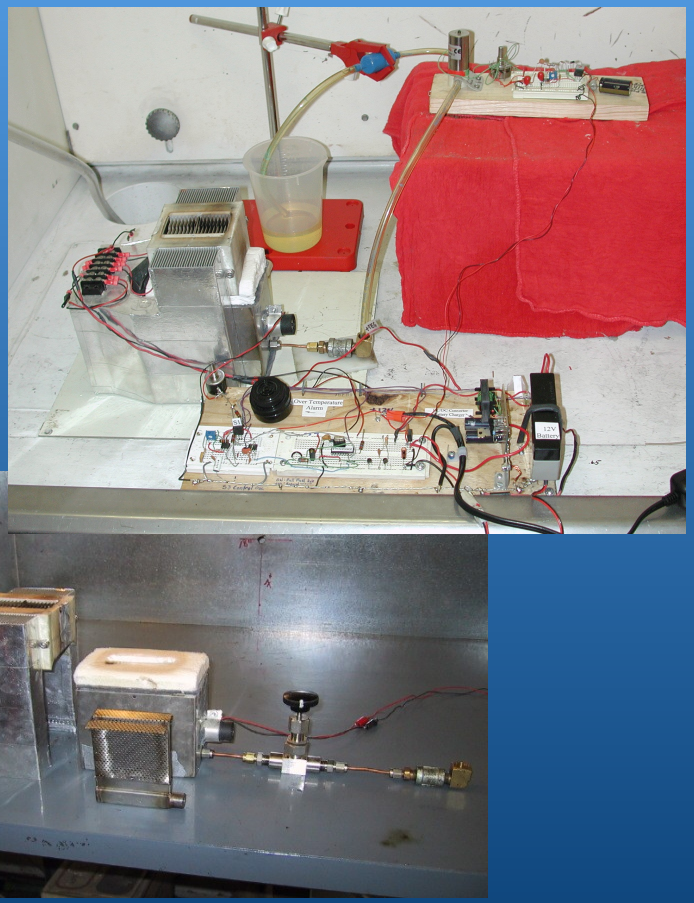
- “Hair Curler” butane burner
- Graphite foam hot side heat exchanger
- Aerogel insulation
- Foam aluminum cold side heat exchanger
- Swiss-made miniature efficient fan
- Capability of 100 W-hr/kg

Thermoelectric Generator

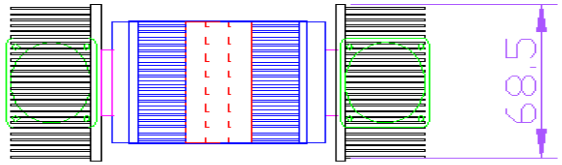


Tasks 1-4 – STEG-2

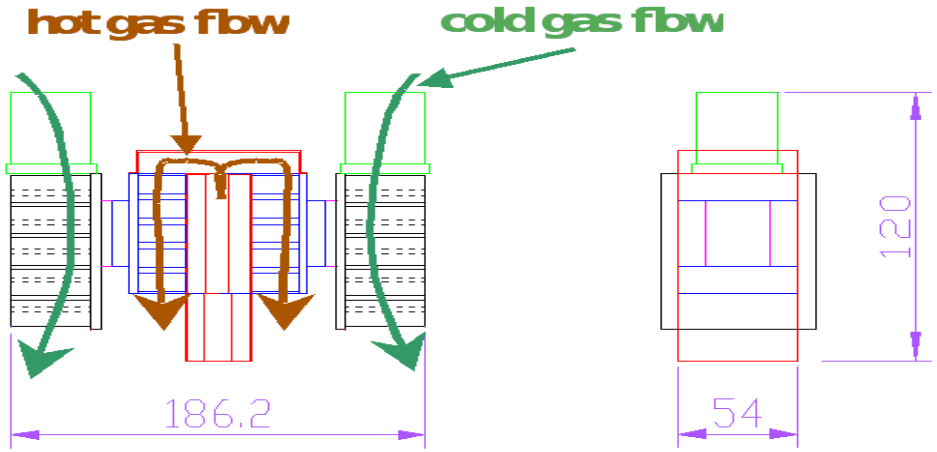
- Power output, gross 4.5W
  - Cooling fan 1.2W
  - Combustion fan 0.06W
  - Fuel pump 0.10W
  - DC-DC converter 0.47W
- Power output, net 2.7W
- Fuel consumption 0.5ml/min
- Input heat 250W
- TH / TC 260ºC / 60ºC
- Fuel conversion efficiency,
  - net 1.1%
  - gross 1.8%
- Ref. module efficiency 4%
- Fuel energy to module 45%



Tasks 1-4 – STEG-3

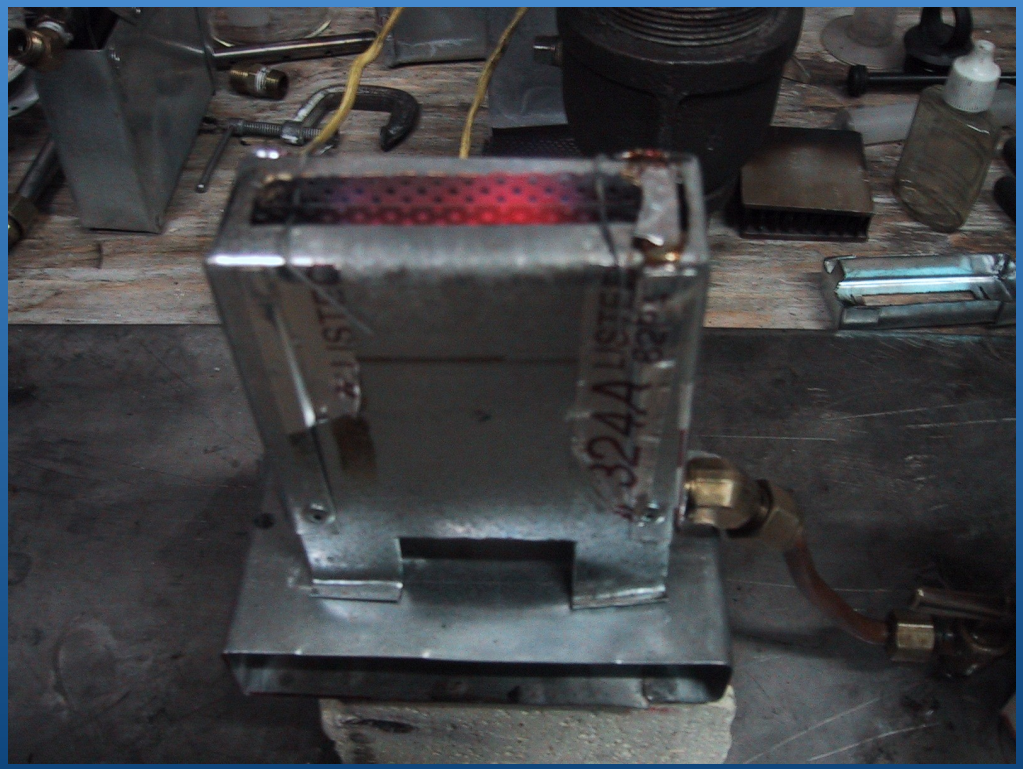


burner
t. e. module
hot side HX
cold side HX
fan



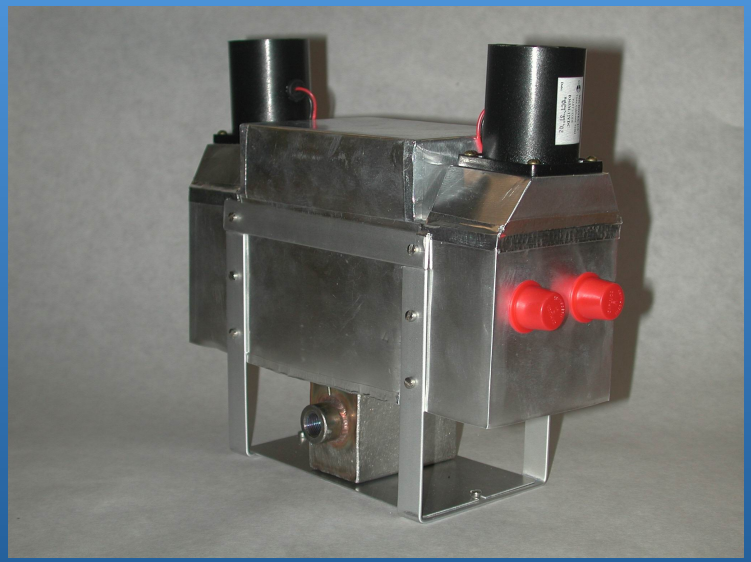
Tasks 1-4 – STEG

"Slot" burner developed by Altex Technologies Corp.

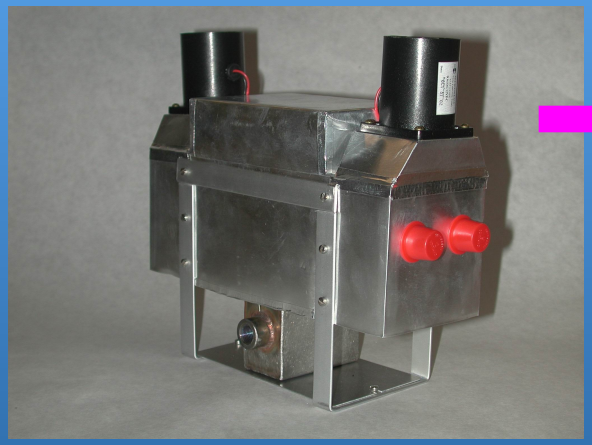


Tasks 1-4 – STEG-3

- Power output, gross 2.0W
  - consumed to operate 0.5W
- Power output, net 1.5W
- Fuel consumption 0.33ml/min
- Input heat 165W
- TH / TC 260ºC / 65ºC
- Fuel conversion efficiency,
  - net 0.9%
  - gross 1.2%



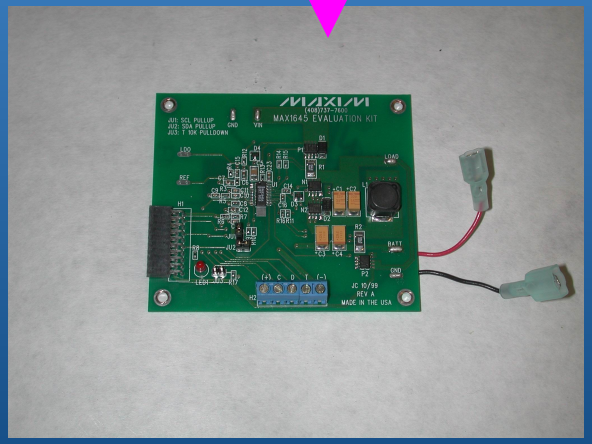
STEG as Charger

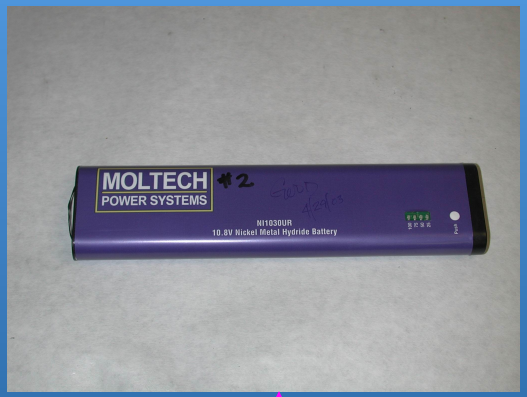


12V

?

24V





11V

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Tasks 1-4 – STEG

	STEG-2	STEG-3
power	2.7W	1.5W
weight	2.3kg	1.1kg
power/weight	1.2	1.4
volume	6.8ℓ	5.0ℓ

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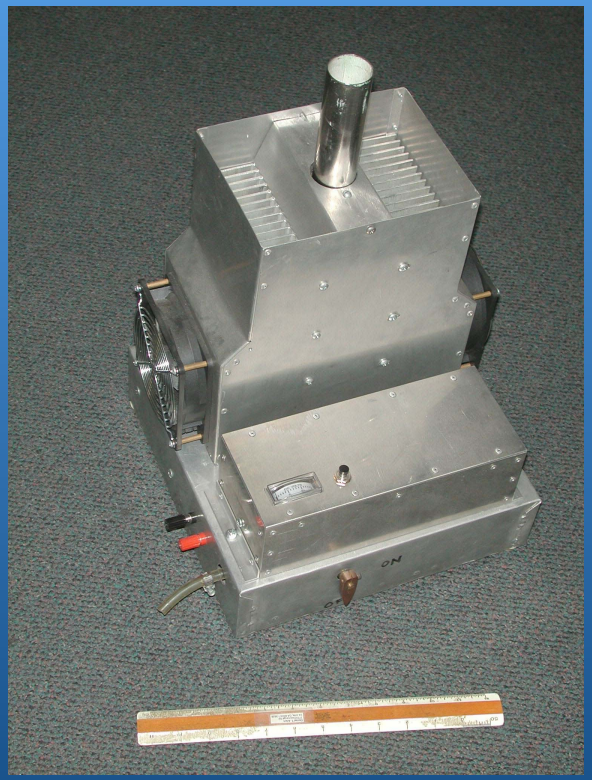
Status of STEG

- Voltage interface issue for “smart” (SMBus) battery charger circuits
- Optimum stable operation
- Electric start demonstration
- Circuit board
- Controls
- Fuel tank
- Unit Packaging

Task 6 – 15-20 Watt Generator

- Burner being made and tested at Altex
- Existing generator (originally propane-fueled) and power conditioning system being modified to fit



Task 5 – 15-20 Watt Generator

Selected Rechargeable Batteries

rechargeable battery or cell	type	volts	capacity*		W to charge in 4 hrs.	hrs. to charge at 2 W	hrs. to charge at 17.5 W
			A-hr	W-hr			
BB-2590	Li-ion	28.8	5.1	147	37	74	8.4
BB-388	Ni-MH	13.2	1.6	21	5	10.5	1.2
BB-390	Ni-MH	12/24	3.7 - 5.4	89 - 130	22 - 32	44 - 65	5.1 - 7.4
BB-590	Ni-Cd	12/24	2.3	55	14	27	3.1
NI1030UR	Ni-MH	10.8	1.03	11	2.8	5.6	38 min
D201	Li-ion	11.1	4.8	53	13	27	3
BB-2847	Li-ion	8	4.0	32	8	16	1.8
BB-2600	Li-ion	8	3.5	28	7	14	1.6

Selected Army Device Power Needs

Item	power	note
AN/PRC-126 squad radio	13.2 W	uses BB-388
EPLRS (Enhanced Position Location Reporting System)	16 W	
NTDR (Near Term Digital Radio)	< 20 W	
SINCGARS (Single Channel Ground and Airborne Radio System)	5 W continuous 50 W sending	uses BB-2590

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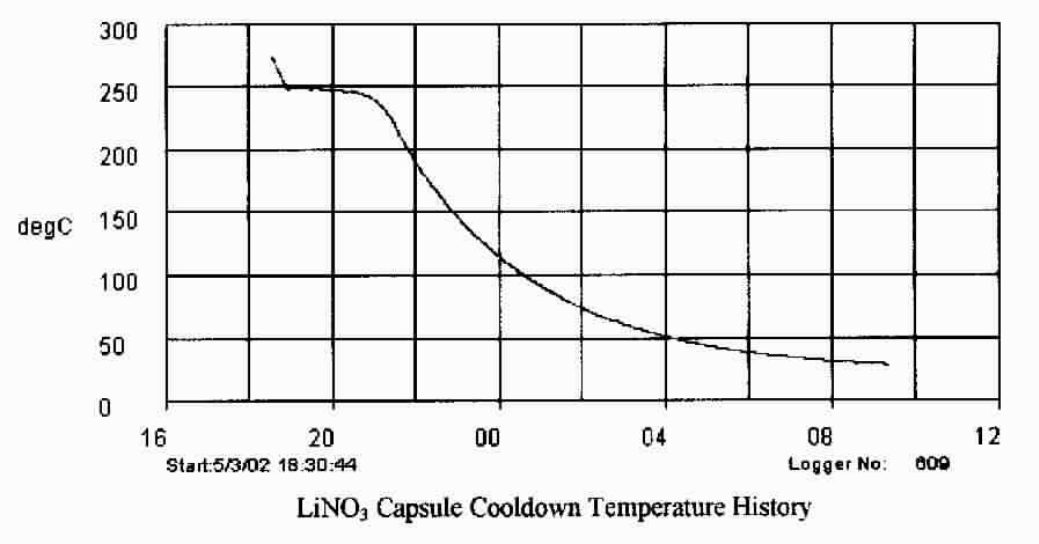
Task 8 – Heat of Phase Change (Molten Salt) Generator

- Detailed generator design completed
- Phase change material selected after further tests: $LiNO_3$



$LiNO_3$ Capsule Cooldown Temperature History

Task 8 – Heat of Phase Change (Molten Salt) Generator

Molten Salt Test

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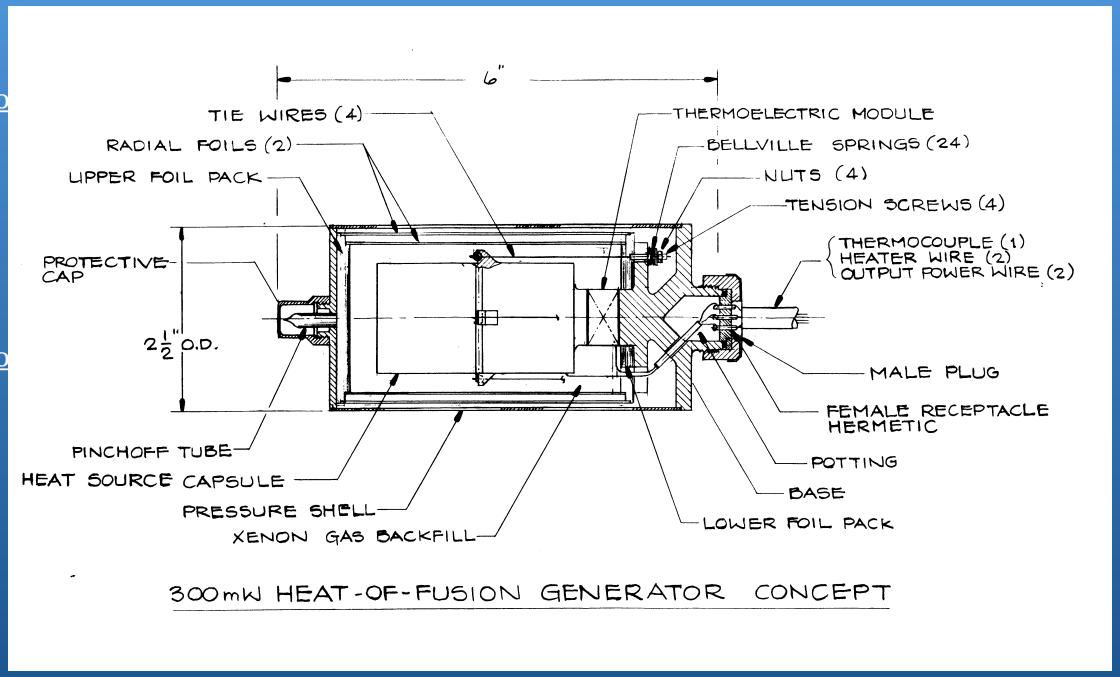
Task 8 – Heat of Phase Change (Molten Salt) Generator

Candidate Compounds

- $LiNO_3$
  - Melting point 250 to 264º
  - Heat of fusion 367 J/g
  - Volume required for 4 hours 119 cm^3
- $FeCl_3$
  - Melting point 304 to 306º
  - Heat of fusion 266 J/g
  - Volume required for 4 hours 135 cm^3
- $NaNO_2$
  - Melting point 271ºC
  - Heat of fusion 217 J/g
  - Volume required for 4 hours 221 cm^3



300mW HEAT-OF-FUSION GENERATOR CONCEPT

Task 8 – Heat of Phase Change (Molten Salt) Generator

- Components fabricated/procured; partly assembled

Complete Assembly

Priorities for Remaining Work

- Final report
- STEG prototype design
- 15-20 W generator demonstration
- Custom module spray-on leads test with mask
- Run 300mW diesel-heated generator (Altex fuel cell project)
- STEG delivery to Army
- Finish and run Phase Change (Molten Salt) Generator

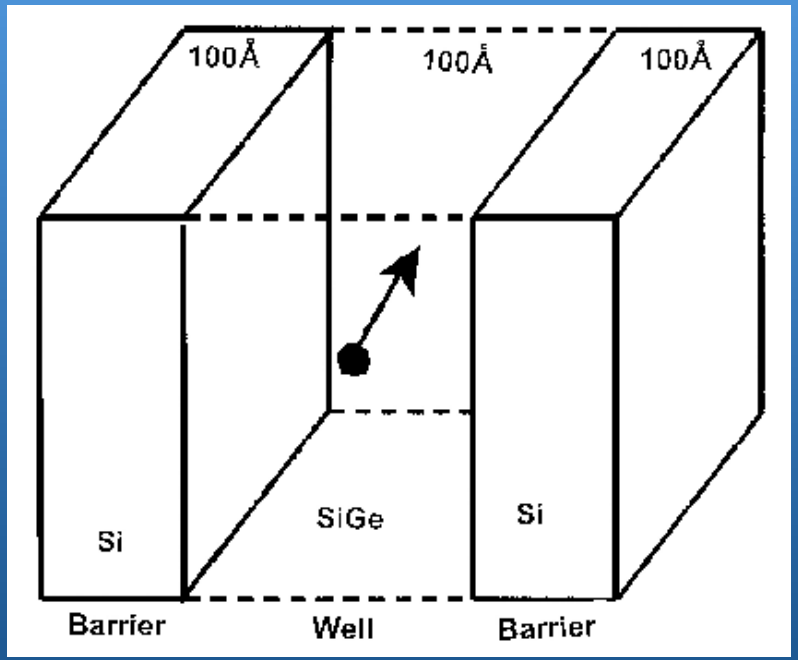
Swedish Army Generator

Quantum Well TE

- Quantum-well confinement in multilayer films is achieved by the electron containment between adjacent barrier layers
- Active layer (the well) is sandwiched between materials with band offset to form a barrier for the charge carriers
- Improvement in Z from an increased Seebeck coefficient (α) and from an increase in the density of states
- Significant reduction on resistivity (ρ) because of quantum confinement
- Significant reduction on thermal conductivity (κ)
- Quantum well (QW) effects become significant as the thickness of layer <200Å

Two-Dimensional Quantum Well TE

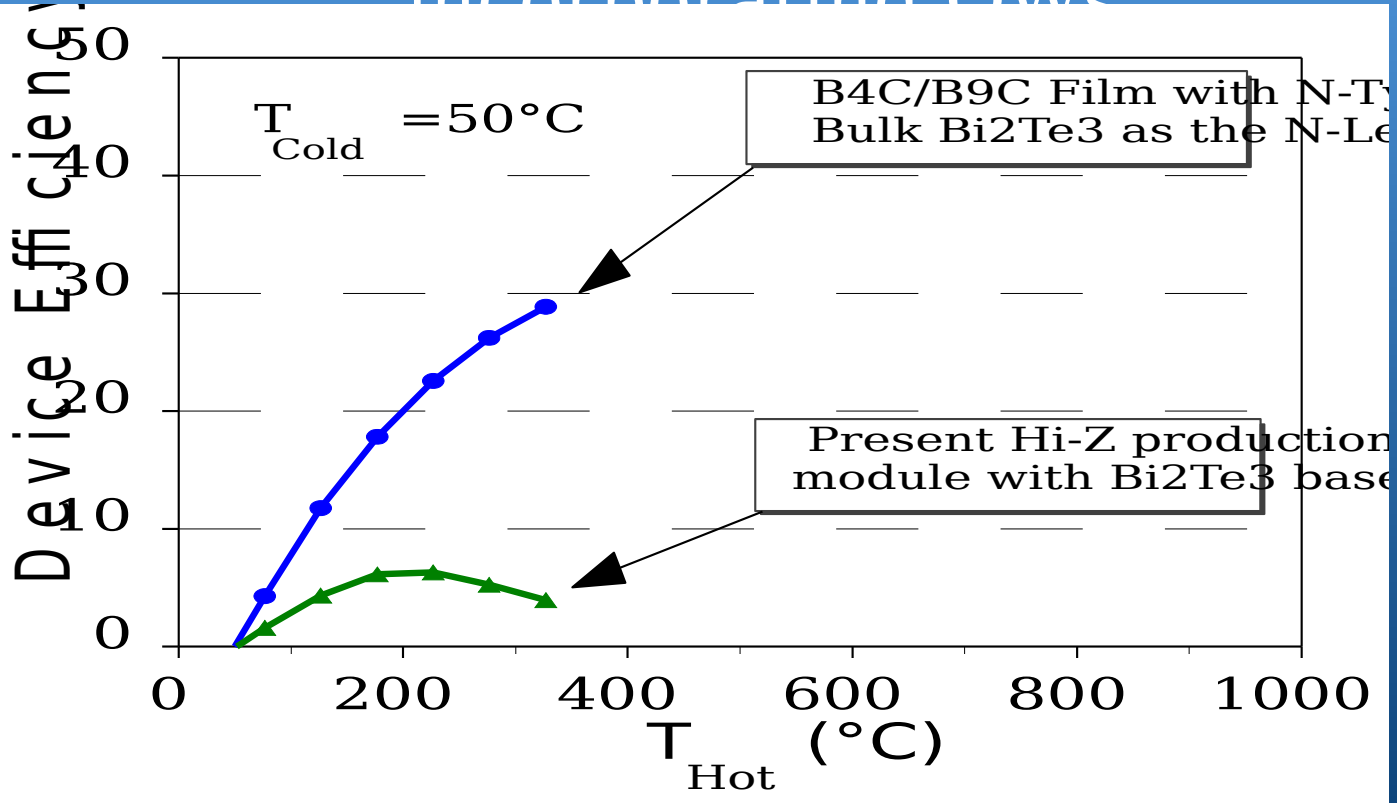
- Active layer sandwiched between materials with band offset to form a barrier for the charge carriers
- Increased Seebeck coefficient (α) due to an increase in the density of states
- Significant reduction on resistivity (ρ) due to quantum confinement of carriers
- Significant reduction on thermal conductivity (κ) due to strained lattice and other factors
- Quantum Well (QW) effects become significant at a layer thickness of <200Å



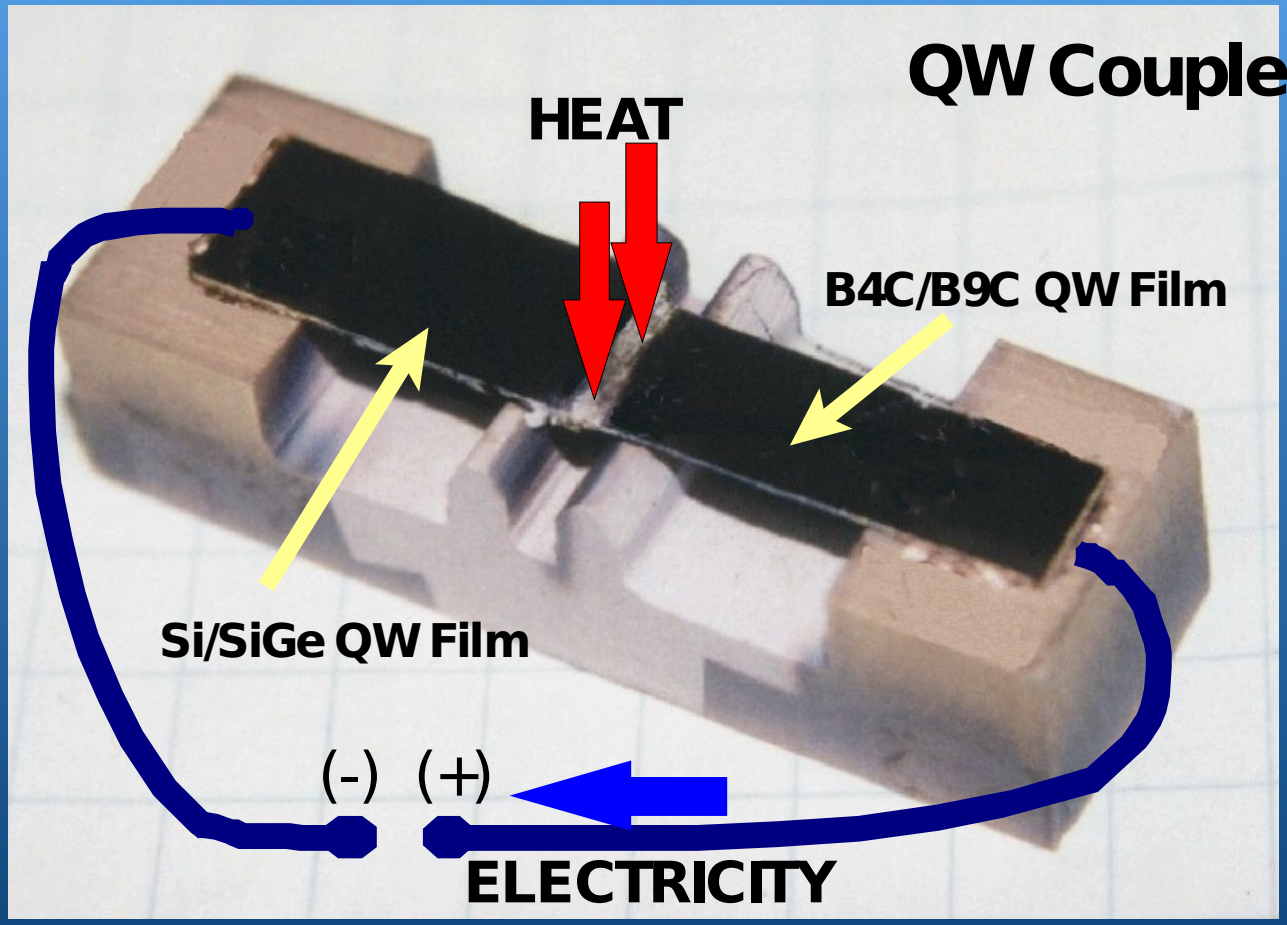
$$Z = \alpha^2/\rho.\kappa$$

Efficiency of B_4C/B_9C Mutilayer Films

Comparison of presently fabricated module and potential modules incorporating QWs



QW Experimental Couple



5 m Si Substrate
11 m B_4C/B_9 -Si/SiGe

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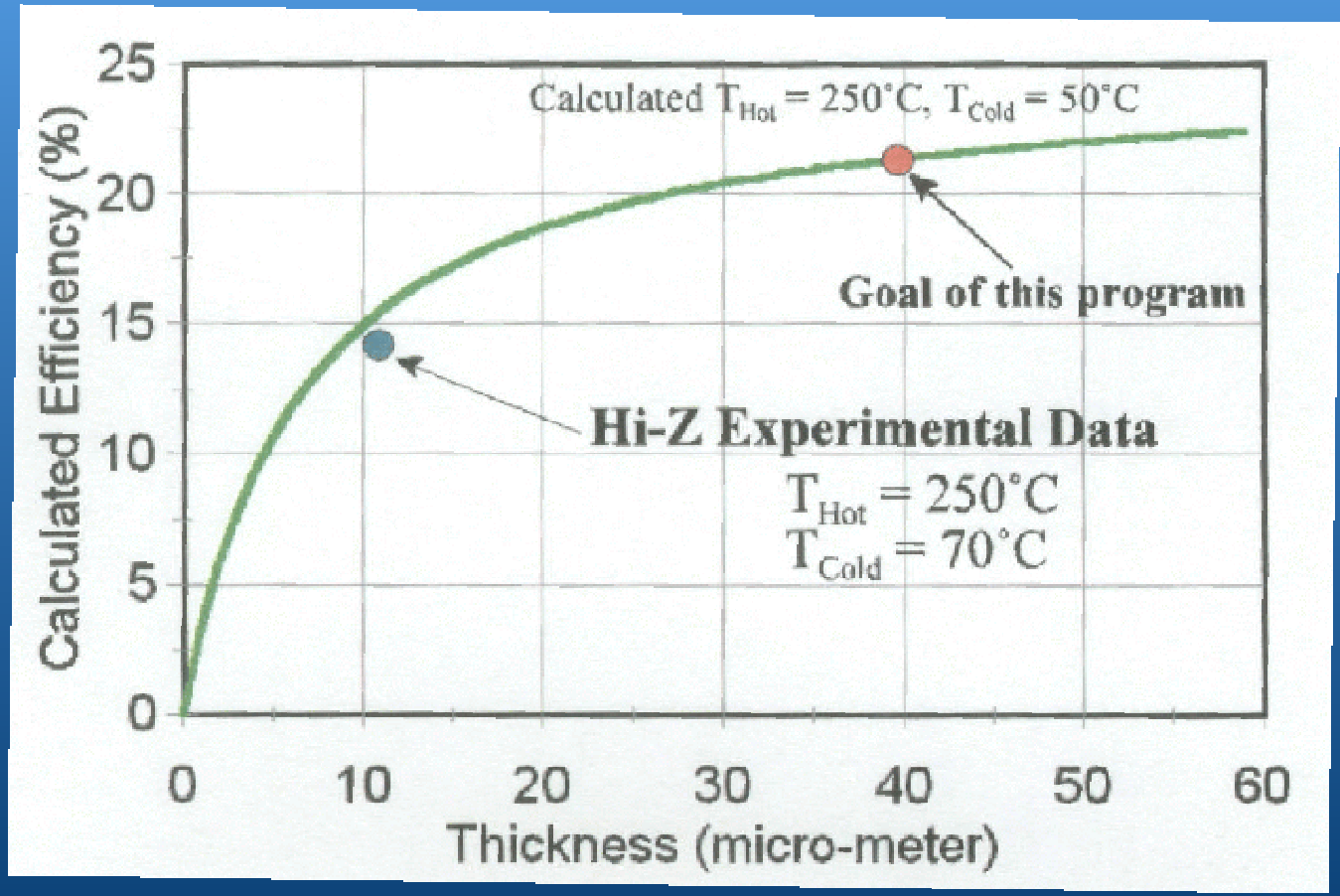
Recent Efficiency Measurement on QW Couple



11 µm QW films on 5 µm Si substrate

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QW Device Raw Test Data

11 μm thick B_4C/B_9C and Si/SiGe on 5 μm Si

$T_{cold} = 70°C$ $T_{hot} = 250°C$

	Power Into Heater			Power Out From Couple			Efficiency
	Voltage	Current	Power	Voltage	Current	Power	
B4C/B9C-Si/SiGe	0.1413V	47.1 mA	6.657 mW	0.365 V	2.608 mA	0.952 mW	14.30%
Calibration: Bi2Te3 Alloys	2.510	0.836 A	2.098 W	0.034 V	3.15 A	0.107 W	5.10%

Back Calculated ZT = 4

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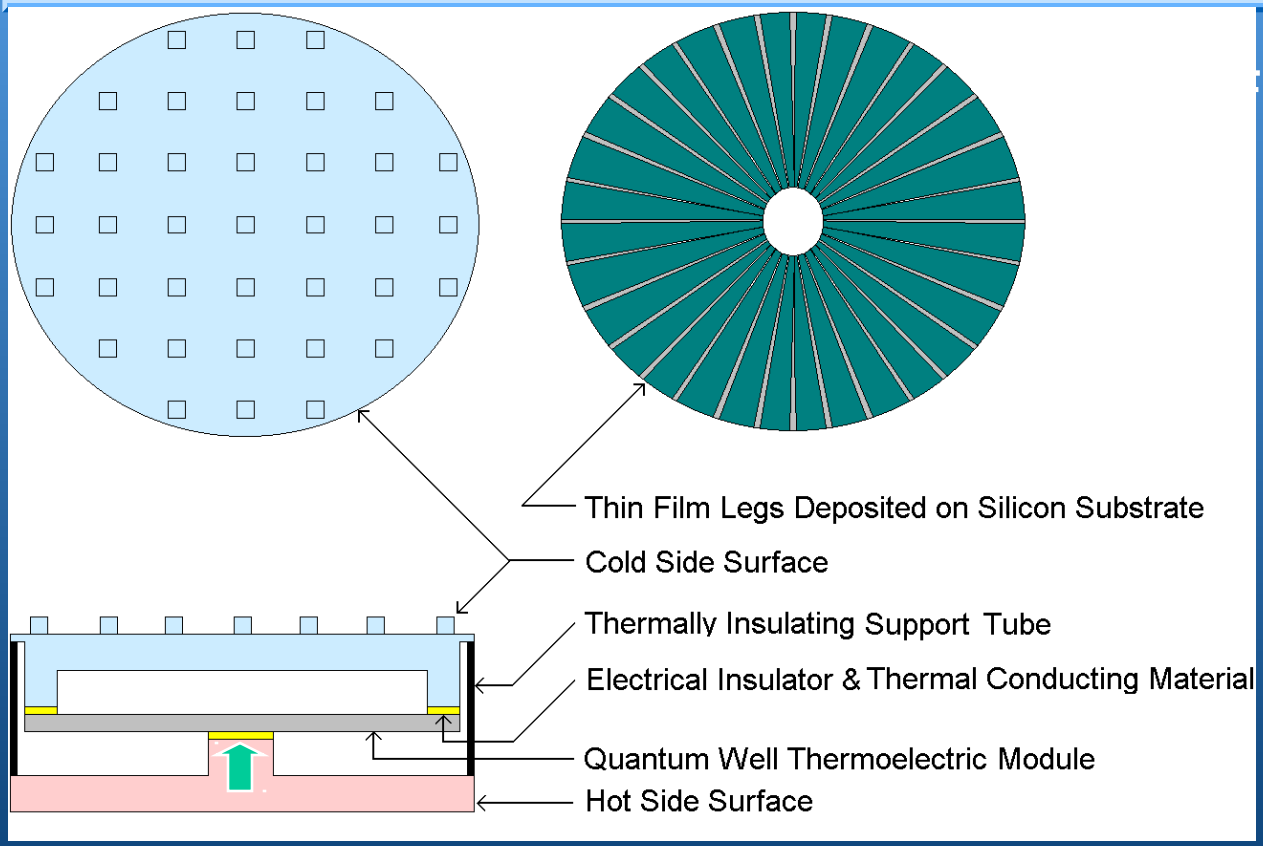
Power Harvesting QW TEG Concept for Navy Shipboard Wireless Sensors


Thin Film Legs Deposited on Silicon Substrate
Cold Side Surface
Thermally Insulating Support Tube
Electrical Insulator & Thermal Conducting Material
Quantum Well Thermoelectric Module
Hot Side Surface

Small size (< 1 in³) requirement satisfied using QW TEG

Provides power for wireless sensors:
5 mW at 3 V using 41°C ΔT from ship interior thermal environment

Generator dimensions: 1 in² footprint, ½ cm height

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